NUTRIENTS IN PORT PHILLIP BAY: WHAT HAS CHANGED IN 15 YEARS?

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Various aspects of the nutrient status of Port Phillip Bay have been studied over the past 15 years by government agencies including the Environment Protection Authority (EPA) and the Marine Science Laboratories (MSL). The results of these studies, each of which had different objectives, are summarised in this paper. Partly because sampling design varied with each study, it is not possible to detect significant changes in the nutrient status of the Bay during the past 15 years.

PORT PHILLIP Bay is a shallow basin with a mean depth of 14 m and a maximum depth of 22 m. Nearly 350 point sources discharge to the Bay, with the Yarra/Maribyrnong and Werribee river systems being the largest freshwater sources (MMBW/FWD 1973). Annual evaporation approximates annual streamflow (about 5% of mean Bay volume) and, except near discharges, salinity is close to oceanic levels. In Corio Bay, where evaporation exceeds freshwater inflow, water is often hypersaline.

For many years, concern has been expressed about: (1) the potential for the Bay to become eutrophic as a consequence of excessive addition of nutrients; and (2) the effect which eutrophication may have on beneficial uses of the Bay (MMBW/FWD 1973). Such concerns have determined the direction of all nutrient studies.

In this paper the results of monitoring programs carried out by the EPA and MSL over the past 15 years (1975–1977, 1980–1984, 1985–1986 and 1985–present) are summarized, and suggestions are made on ways to obtain the information needed for a comprehensive understanding of the effect of nutrients on the Bay ecosystems.

EPA 1975–1977

The State Environment Protection Policy (SEPP) for waters of Port Phillip Bay, declared in 1975, defined water quality standards for the Bay and set objectives against which water quality could be measured. Beneficial uses (such as aesthetic enjoyment, maintenance and preservation of natural aquatic ecosystems, production of fish) were to be protected by the licensing of point source discharges and monitoring of the Bay waters. However, licence conditions are set without knowledge of the effects of the discharge in the discharge zone.

In the SEPP the Bay was divided into nine segments (Kowarsky 1992, fig. 1) on the basis of nutrient concentrations determined in the first major study (1969–1970, MMBW/FWD 1973). A grid of potential sampling sites was designed for each segment, and water was sampled from near-surface, mid-water and bottom water depths at four randomly selected sites within each of the segments at about six-weekly intervals during October 1975–March 1977. Many of the potential sites were not sampled, while some were sampled more than once. Each sample was analysed by MSL for salinity, temperature, dissolved oxygen, pH, suspended solids, nitrate, nitrite, ammonium, total phosphorus, reactive phosphorus and phytoplankton pigments.

Variations in nutrient and chlorophyll concentrations with water depth were minimal, except for samples from the Werribee segment where highest concentrations occurred near the surface (EPA 1979). Nutrient concentrations varied so much within segments that no regions of homogeneous water quality were found in any segment. The highest variability was in those segments (Werribee, Hobsons Bay) with the largest fresh water discharges. These were also the segments with the highest mean nutrient concentrations.

A statistical analysis of the concentrations of three water quality indicators (ammonium, nitrate and total phosphorus) showed that variance within segments was often higher than variance between sampling times (Table 5.5 in EPA 1979). Random stratified sampling is not the most appropriate sampling regime for detecting trends in time (though that was not the objective of the program). When compared with the SEPP objectives, compliance for total phosphorus and chlorophyll *a* was poor in almost all segments; the cruise mean average compliance was 68% for total phosphorus and 41% for chlorophyll *a*. Compliance for other indicators (dissolved oxygen, pH, water clarity) was generally good.

EPA 1980–1984

The second water quality monitoring program carried out by EPA was again concerned with compliance of water quality indicators with the SEPP objectives; surface waters only were sampled. During June 1980–May 1982 samples were collected monthly from a site selected randomly from within each of 16 strata (Fig. 1). The majority of the strata (11 out of 16) were located in the north and western one-third of the Bay; the data averages from this study are therefore biased toward the more industrialized areas of the Bay.

Total organic carbon, Kjeldahl nitrogen and silicate concentrations were also determined.

The results in summary are as follows.

(1) Compliance with the SEPP objectives for chlorophyll *a* was better in all segments than it had been in the 1975–1977 study.

(2) In the Exchange segment, which has a more stringent chlorophyll objective than other segments, only 50% of observations met the objective.

(3) Average compliance for dissolved oxygen in surface waters was lower in 1980–1982 than in 1975–1976 (67% compared with 84%).

(4) Inorganic nitrogen 90th percentile concentrations were higher in the Yarra mouth during 1980–1982 than during 1975–1976, while total phosphorus 50th concentrations were higher in all strata during 1980–1982.

(5) Average compliance for total nitrogen was greater than 95%.

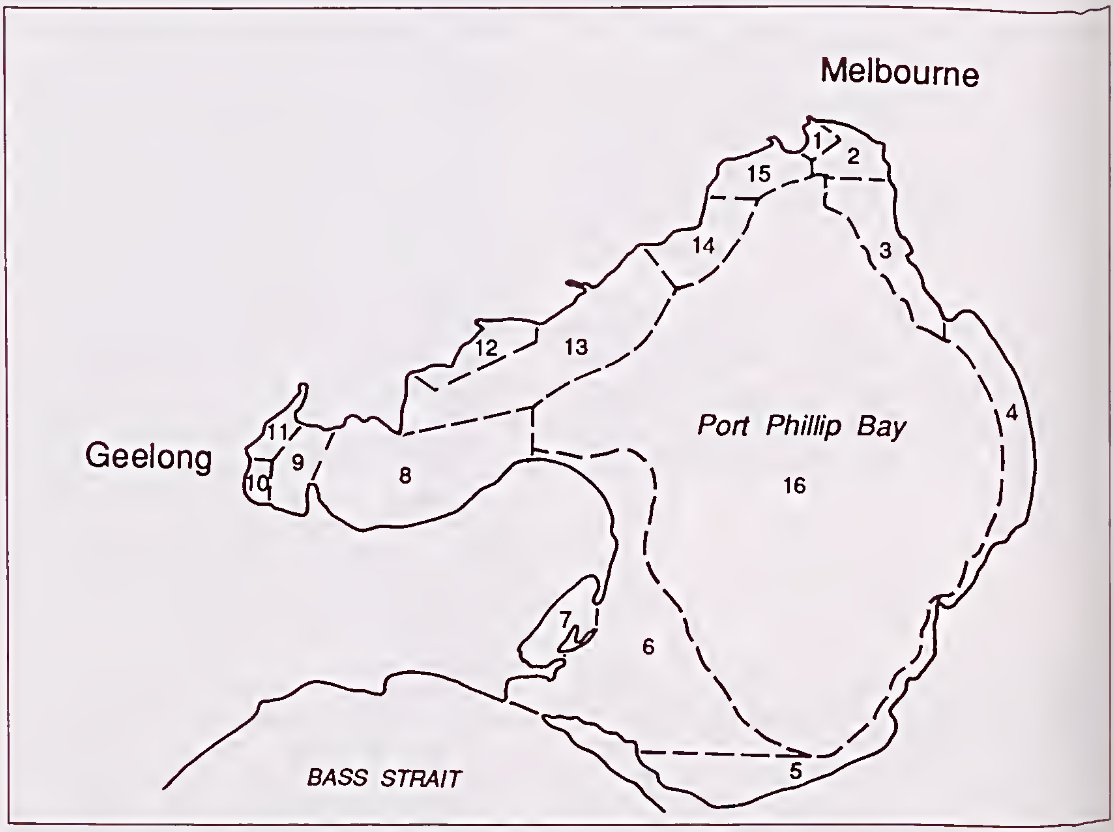

Fig. 1. Strata of Port Phillip Bay sampled during 1980–1986.

Sampling continued during October 1982–June 1984 in the same format as for 1980–1982 and the analytical results of all 48 cruises (1980–1984) have been summarized (Cowdell et al. 1985).

During 1980–1984, highest mean reactive phosphate and inorganic nitrogen concentrations occurred in stratum 12 (Werribee Farm), while mean chlorophyll *a* concentrations were highest in strata 1 and 2 (Hobsons Bay; 2.6–2.7 μg L^{-1}). Chlorophyll *a* concentrations were lowest in strata 5 and 6 (South-Eastern and Exchange; 0.7 μg L^{-1}), while strata 12 and 13 (Werribee segment) were intermediate in concentration (2.2–1.2 μg L^{-1}). There was no direct correlation between areas of high nutrient concentration and areas of high chlorophyll concentration. Mean Secchi disc depth was low in the Yarra mouth and Hobsons Bay (strata with highest mean chlorophyll *a* concentrations), suggesting that turbidity did not limit phytoplankton growth during 1980–1984. This contradicts the argument advanced by the EPA (EPA 1983) that increased runoff during 1980–1982 led to greater turbidity in the Bay, limiting phytoplankton growth. Conversely, mean chlorophyll concentrations were too low (less than 10 μg L^{-1}) to make a significant contribution to light attenuation (Kirk 1976); low Secchi disc depths indicated high inorganic particulate loads.

When a volume-weighted correction is made to compensate for most of the measurements being made in relatively shallow near-coastal waters, baywide annual mean chlorophyll *a* concentrations increased significantly (by analysis of variance with multiple t-tests at the 5% significance level) from 1980/81 to 1981/82, and from 1982/83 to 1983/84, with a statistically non-significant decrease from 1981/82 to 1982/83. The mean chlorophyll *a* concentration over the period was 0.79 μg L^{-1}.

EPA/MSL 1985–1986

During July 1985–June 1986, water quality data for Port Phillip Bay were obtained from quarterly sampling at 28 fixed sites throughout the Bay; from monthly sampling at 4 sites in the Central segment; from hourly sampling for one 24-hour period in Corio Bay in July 1975 and January 1976; and from on-board analysis of water collected continuously during 4 cruises (August and November 1985; February and May 1986) along transects across the Bay (Longmore et al. 1990). As well as collecting samples for comparison with the SEPP objectives for Port Phillip Bay, the objectives of this study were:

(1) to determine spatial and temporal trends in water quality; and (2) to determine, through studies of effluent plumes, the extent and pattern of influence of major inputs of river water or effluents on water quality.

Spatial and temporal trends

Total phosphorus concentrations at the 28 fixed sites varied little over the year, except off the Werribee Treatment Complex (WTC) where concentrations were highest in winter. Similarly, ammonium and nitrate concentrations were highest off the WTC in winter and very low in summer. The Yarra River discharged inorganic nitrogen throughout the year, and the Werribee River was an important source of nitrate during winter. Chlorophyll *a* concentrations were generally twice as high during the winter months, and were highest off Werribee in winter–spring.

Plumes

The extent and pattern of influence of major inputs of fresh water and effluents on water quality of the Bay is not well known. The program was designed to provide information on the influence of inputs from the Yarra River, Werribee River, WTC, sources in Corio Bay and the Patterson River.

Continuous on-board analysis showed that the Yarra River created a larger fresh water plume than the Werribee and Patterson rivers and the WTC. The Yarra River plume affected salinity predominantly on the eastern side of the Bay. During August 1985 the plumes of fresh water from the Yarra River, Werribee River and the WTC clearly affected the salinity of at least half of the surface waters of Port Phillip Bay (Fig. 2).

Phosphate discharge from the Yarra River was evident on all cruises but its effect was not observed much beyond Hobsons Bay. The input of phosphate from the WTC exceeded all other point discharges during autumn and winter, and affected the western one-third of the Bay.

Nitrate plumes were negligible during summer but were detectable off the WTC in spring and autumn, off Werribee River in winter, and in Hobsons Bay on all cruises.

Highest chlorophyll concentrations were observed off WTC in winter, spring and autumn.

Overall compliance of the water quality data

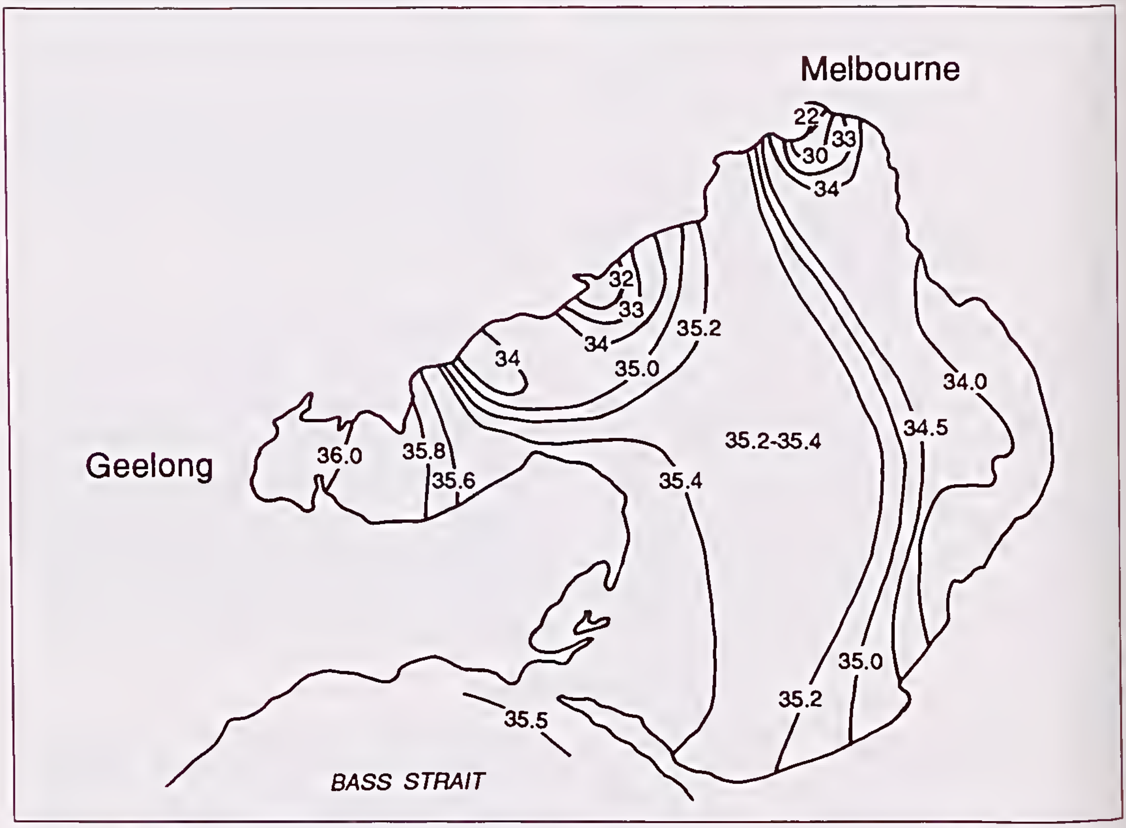

Fig. 2. Effect of fresh water discharge on surface salinity of Port Phillip Bay during August 1985.

with SEPP objectives was similar to the compliance in 1980–1982; compliance for concentrations of total phosphorus and chlorophyll *a* in water samples from all segments of the Bay was poor. In winter, no sample from any segment met the chlorophyll objective. Typical chlorophyll concentrations were 2–6 times the objective.

LOOKING FOR TRENDS

Given that the SEPP objectives were drawn from the mean concentrations of nutrients found during the 1969–1970 study, it is important to explain why in all studies since 1975 chlorophyll and total phosphorus concentrations have failed to meet the objectives. Was 1969–1970 a period of low nutrient concentrations and low plankton production, or have concentrations increased since then? Can we be certain that the differences in nutrient and chlorophyll concentrations observed in the Bay since 1969 are not due to different analysts and/or different methods? In a summary of the data collected to date from the central segment of the Bay (which contains 57% of the surface area and 80% of the volume of the Bay, and is the only segment to have been sampled in all studies listed here), it is difficult to distinguish a trend in either chlorophyll *a* or inorganic nutrient median concentration with time (Table 1). We could conclude that, at least in the centre of Port Phillip Bay, there is no evidence for concern about the effects of current nutrient discharges. Shallower waters close to coastal discharges have not been studied over the same period of time, and the effect of nutrients on productivity close to the Bay shore is not yet understood.

Because of the discontinuous nature of the data gathered before 1984 it was not possible to apply time series analytical techniques to determine statistically significant temporal trends. However, Saunders & Goudey (1990) pooled chlorophyll *a* concentrations by stratum and showed that the data gathered from segments of the Bay are not normally distributed. Using a

Study	PO_4	NH_4	NO_{2+3}	SiO_4	Chl*a*	Salin.	Temp.
1969–1970 (1)	2.1	3.6	0.6	0.5	1.2	34–37.4	11–22
1975–1976 (2)	1.7	0.4	0.1	—	1.1	—	—
1975–1977 (3)	1.9	0.5	0.3	—	1.5	31.1–37.4	10–22
1980–1984 (4)	1.9	0.2	0.1	3.7	0.8	31.2–38.8	8.5–23
1985–1986 (5)	1.9	<0.1	<0.1	1–11	1.2	34.8–35.7	10–21
1987–1989 (6)	2.0	0.5	0.1	7.0	1.1	34.3–35.7	10.3–21

Table 1. Comparison of results from the central segment of Port Phillip Bay. Median nutrient concentrations in µM, chlorophyll *a* in µg L^{-1}, temperature in °C. Study key: (1) = Phase 1, MMBW/FWD (1973); (2) = Axelrad (1978); (3) = EPA (1979); (4) = Cowdell et al. (1985); (5) = Longmore et al. (1990); (6) = Mickelson (1990). Note that median ammonium (NH_4) and oxidized nitrogen (NO_{2+3}) concentrations reported in Phase 1 were far higher than those measured since, and salinity and temperature extremes have varied from study to study but not necessarily from year to year. Random site selection and inadequate sampling frequency means extremes may have been missed.

non-parametric seasonal Kendall test, a statistically significant decline in chlorophyll *a* concentration was observed during 1975–1986 in the Corio Urban stratum, and significant increases in chlorophyll concentration were detected in the Werribee Farm and Altona strata. This analysis assumes that: (1) the effect of variation due to location within a segment (or stratum) can be neglected if sufficient random samples are collected within each segment; and (2) the sampling intensity and variance within each segment is the same over time. A more robust analysis could be made if variation due to location could be ruled out completely by sampling at geographically fixed sites.

EPA FIXED SITES 1984–PRESENT

In 1984 EPA began regular (2–4 weekly) monitoring at three fixed sites in the Bay: Hobsons Bay, Corio Bay and central Port Phillip Bay. A recent analysis of the data (D. Robinson, pers. comm.) using a Kendall test of association found that there were increasing trends in most indicators monitored. During 1984–1989 significant increases in total phosphorus concentrations occurred only at the Bay centre and Corio Bay sites. There were no statistically significant changes in chlorophyll *a*, dissolved oxygen, phosphate or inorganic nitrogen concentrations. Upward (non-significant) trends were observed in total nitrogen concentrations.

The same analysis could not be extended to data gathered before 1984, since all previous sampling programs were based on random sampling within each segment, introducing variation due to location within the segment.

It is reasonable to ask whether the total nutrient input to the Bay (as distinct from nutrient concentrations in the Bay) has increased during the past 15 years. Estimates by Melbourne Water of nitrogen and phosphorus loads from the WTC to the Bay suggest that loads have increased by less than 15% since 1975. EPA fixed site river sampling, particularly in the Yarra River, indicated the same general increasing nutrient concentration trend during 1984–1989 as was observed for the fixed sites in the Bay (that is, an increasing trend in nitrogen and phosphorus concentrations in most rivers entering the Bay, but the only significant trend was for total phosphorus). However, neither of these studies have taken into account the effect of storm events, during which a large proportion of annual nutrient load may be transported. Work is proceeding to determine the current influence of storm events in streams and the WTC, but the following questions remain. Can load estimates be corrected for past storm events? Are past estimates of nutrient load meaningful?

Following intensive connection of unsewered residential areas of Melbourne to the sewer during the 1970s and EPA licensing of industrial discharges, the water quality of Port Phillip Bay was expected to improve; there is no firm evidence that this has happened.

FUTURE DIRECTIONS

To understand better the effects of nutrient inputs on the Bay, the following is needed:
(1) a more complete data set (both from nutrient inputs and from Bay waters) to determine *long-term trends*;
(2) an accurate measure of the *areas of the Bay impacted most* by nutrient inputs;
(3) cheaper *sampling strategies*;
(4) better understanding of nutrient cycling

between water, sediments and biota of the Bay;
(5) *better indicators* of water quality, with emphasis on an early warning of trends toward eutrophication.

Long-term trends

MSL is responsible for the management of the estuarine and marine fisheries of Victoria. A monitoring program of fixed sites was recently commenced by MSL to determine nutritional and physicochemical factors which affect the food chain in Port Phillip Bay at its lowest level (plankton). Regular water sampling in six areas of high fishing pressure in Port Phillip Bay will permit the use of time series analytical procedures for examining long-term trends in ambient water quality. This work will thereby complement the EPA Fixed Sites program. With some further work to define the effect of flood events, the EPA river monitoring program and monitoring of the Werribee Treatment Complex by Melbourne Water should allow us to determine trends in inputs to the Bay.

Areas impacted most

When plankton die they settle to the bottom of the Bay and decay, producing a sediment oxygen demand (SOD). Increasing nutrient supply which leads to increased algal biomass should be reflected in an increased SOD. If waters are stratified, SOD may cause decreases in oxygen concentration (hypoxia) below the pycnocline, which in extreme cases could have catastrophic effects on, for example, scallop spat (Body & Murai 1986). While recent Melbourne Water/MSL work showed that water in central Port Phillip Bay is rarely hypoxic (Mickelson 1990), no measurements of SOD had been made elsewhere in the Bay. A bay-wide survey of SOD carried out in 1991 will, when analysed, assist in identifying those areas of the Bay currently impacted most by nutrient inputs and the possibility of their being affected by hypoxia.

Sampling strategies

Sampling of Bay waters from boats and subsequent chemical analysis is expensive. Sentinel organisms have been used for estimating the cumulative effect of heavy metals and hydrocarbons on the biota of the Bay. However, indicator organisms are not used for nutrients; all nutrient sampling programs to date have involved water analyses only. Effort could be directed into identifying possible indicator organisms (e.g. macroalgal biomass) or techniques (e.g. fouling plates), saving both time and effort. Sediments may also act as integrators of nutrient input, through their role in the storage and recycling of organic matter which settles to the bottom, and it may be possible to use infrequent sediment surveys to monitor long term trends in organic supply or oxygen demand, or to detect biomarkers in sediment.

Better indicators

Are water quality indicators sufficient to achieve the SEPP objectives? Fourteen years ago, Axelrad (1978) demonstrated nitrogen limitation in nutrient enrichment bioassays of phytoplankton from Port Phillip Bay. Phytoplankton require about 15 atoms of nitrogen for each atom of phosphorus and preferentially absorb inorganic nutrients. The mean atomic ratio of inorganic nitrogen to inorganic phosphorus in Port Phillip Bay is about 1:5, emphasising the probability of nitrogen limitation. During all of the surveys taken so far, chlorophyll concentrations in Port Phillip Bay have exceeded the SEPP objectives; on the other hand, total nitrogen concentrations were below the SEPP objectives. If this indicates excessive phytoplankton growth in Port Phillip Bay, and if phytoplankton growth in the Bay is nutrient-limited, then it follows that the SEPP nutrient objectives are too high to prevent excessive algal growth.

There are only two nutrient indicators in the SEPP: total nitrogen and total phosphorus. Over most of the Bay the SEPP for total nitrogen is irrelevant to growth of plankton because more than 90% of the dissolved nitrogen in many segments of Port Phillip Bay is in refractory organic forms unavailable to plankton. However, nutrients in sewage discharges (e.g. from Werribee) are predominantly in inorganic (readily available) forms, and the SEPP for total nitrogen may have some relevance in areas affected by such discharges.

An SEPP for inorganic nitrogen may appear to be more relevant to growth of plankton, but uptake of inorganic nitrogen is rapid close to discharges, and ambient concentrations for the whole Bay do not reflect the input rate or its effect.

It could be argued that, in a nitrogen-limited system without significant N_2 fixers, phosphate is in excess and higher phosphate concentrations are unlikely to cause more algal blooms. Inorganic nitrogen is rapidly taken up by both phytoplankton and benthic plankton, particularly near Werribee (Axelrad et al. 1979); thus increasing phosphorus concentrations over time could be interpreted as the result of an increased discharge of both inorganic nitrogen and phosphorus, with the inorganic nitrogen having been utilized close to the discharge.

Relying on chlorophyll *a* as an indicator may not be satisfactory, particularly on a local scale. For example, Axelrad et al. (1979) estimated that benthic productivity near Werribee was 3–5 times that of plankton in the water column. Effects of nutrient inputs from the WTC may be more easily observed in the benthos than in the phytoplankton.

If management objectives are to keep phytoplankton growth to the SEPP objectives, there needs to be a strategic review. Simultaneously, the quantitative relationships between fish populations and "excess" phytoplankton growth should be determined for the Bay. One of the beneficial uses to be protected is the maintenance and preservation of natural aquatic ecosystems and wildlife; maintaining a particular chlorophyll *a* concentration may not be enough to protect that beneficial use. It is also important to realise that low numbers of toxic phytoplankton may be sufficient to cause enormous problems, without affecting the total chlorophyll *a* concentration. Perhaps the best way to monitor phytoplankton in Port Phillip Bay is by regular counting of each species; MSL is currently doing that.

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